Getting Closer to Fully Coherent Hard X-ray Femtosecond Free Electron Lasers

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We have achieved a crucial step that bridges the femtosecond high-order harmonic generation (HHG) community and the free electron laser (FEL) community. This research provides convincing proof that a femtosecond HHG seed with a wavelength of tens of nanometers can be up-converted in frequency to produce hard x-ray FEL emission with both spatial and temporal coherence. The duration of the seeded x-ray FEL emission is still tens of femtoseconds, almost the same as the HHG seed duration. Thus, fully coherent hard x-ray femtosecond FELs are feasible.

BEAMLINE
BNL-SDL

PUBLICATION
J. Wu, P.R. Bolton, J.B. Murphy, and X. Zhong, "Free Electron Laser Seeded by IR Laser Driven High-Order Harmonic Generation," *Appl. Phys. Letts.*, **90**, 021109 (2007).

FUNDING
U.S. Department of Energy
U.S. Office of Naval Research

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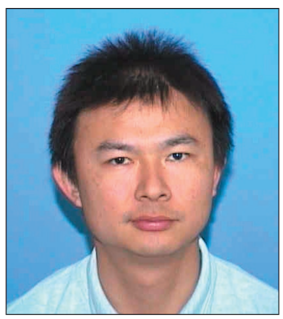

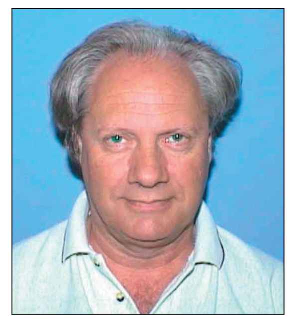

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As scientific research continues to explore the limits of smaller (nanometer and sub nanometer) and faster (femtosecond and attosecond) phenomena, light pulses are commonly used as probing tools. Investigating such phenomena requires a hard x-ray pulse of femtosecond duration or less. Hard x-ray sources exist at light sources around the world. However, their duration is typically tens of picoseconds (one picosecond is 1,000 femtoseconds) because the x-ray pulse duration is determined by the electron bunch duration. Although femtosecond x-ray pulses can be obtained by using only a short temporal slice of an electron bunch, these "sliced" x-ray sources have significantly reduced flux and are incoherent.

Alternatively, in free electron lasers (FELs) electrons of a single bunch wiggle their way through an undulator, initiating instability. Exponential growth of this instability greatly enhances the peak power of the FEL emission toward saturation. FELs are therefore capable of generating light levels that exceed those of conventional synchrotron sources by many orders of magnitude. Yet, the duration of this FEL emission is still comparable to the electron bunch duration. By simply relying on the FEL instability, with a 100-meter long undulator, x-ray FEL emission can have good transverse (spatial) coherence, but lacks longitudinal (temporal) coherence. This is because the FEL instability is initiated by spontaneous undulator radiation, which is not temporally coherent.

A proposed solution is seeded FEL emission, in which the instability is initiated by a coherent seed laser pulse. In this scheme, electrons are modulated by the seed laser such that they know each other's relative phase. Fortunately, FEL emission can also occur at harmonics of the seed laser wavelength. This is crucial, because we can then up-convert the seed laser frequency to hard x-ray regime. However, there are upper limits to the FEL up-conversion factor. In such a seeded FEL scheme, the final FEL pulse duration is determined by the seed laser pulse duration, which can be much shorter than the electron bunch duration.

A promising seed candidate is the high-order harmonic generation (HHG) generated by ultrashort infrared or visible laser pulses in gas targets. The HHG wavelength can be as low as tens of nanometers. But the HHG generation efficiency imposes lower limits to the seed pulse wavelength. So up-conversion in the FEL process by a factor of 100 would bring us to the exciting Angstrom wavelength regime. The HHG pulse duration is typically tens of femtoseconds and the up-converted, seeded FEL duration is comparable.

A more detailed view of an HHG seed pulse shows that it is comprised of many harmonics of the IR (or visible) laser frequency and temporally amounts to a series of attosecond spikes (an attosecond pulse train) as the red curve shown in **Figure 1**. So within the FEL community, the extent to which an HHG seed pulse can drive the FEL instability maintaining phase coherence has been contemplated. This is a challenge for numerical simulation, because one has to numerically resolve the attosecond structure of the unique HHG pulse train. Instead, we took an analytical approach to show that the attosecond structures of the seed pulse would be smeared out within a very short distance inside the undulator. For the example in our paper, at a distance of 18 cm into the undulator, the attosecond structures are almost smeared out as the blue curve in **Figure 1**. The HHG seed would effectively act as a harmonic pulse that is generated via standard wave mixing in a crystal, since the light pulse approaches the smooth green curve very quickly as in **Figure 1**. We further proved that the FEL acts as an extremely narrow band filter to the extent that only one particular harmonic order in the HHG seed pulse interacts with the electron bunch, and experiences exponential gain. The other very important pioneering development in this work is clarification of the noise issue in seeded FELs by distinguishing the undulator amplifier bandwidth and the seeded FEL bandwidth. We present crucial proof that the undulator noise will not significantly degrade the phase coherence of the final x-ray FEL, even after the 100 times up-conversion to the FEL frequency. This has been a concern for years. Finally, we have established convincingly that the HHG-seeded FEL duration would remain almost the same as the original HHG seed pulse duration.

So what have we achieved? — A clear analytical basis that establishes the feasibility of hard x-ray femtosecond FEL emission with both spatial and temporal coherence.

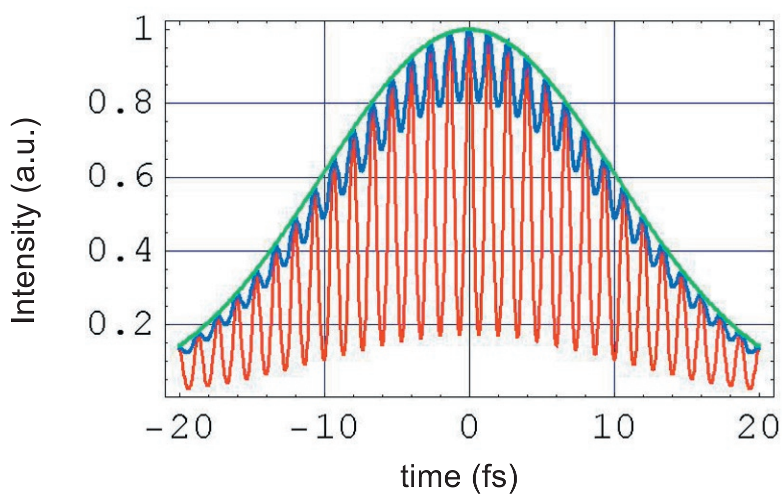

Figure 1. *Illustration of the smearing effect in the FEL process. The red curve is the initial HHG seed pulse with attosecond structures. For the example in the paper, the blue curve is at a distance of 18 cm into the undulator, where the attosecond structures are quickly smeared out to approach the smooth pulse as the green curve.*